

An analytical solution for thermal transport in deep x-ray lithography

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Abstract

Deep x-ray lithography involves the exposure of a resist to synchrotron radiation, in which the photons are absorbed by the resist and substrate materials, and are subsequently converted to thermal heat. With high irradiation intensity, the temperature rise in the system may be large, leading to undesirable thermal stress and distortion. In this study, an analytical solution is reported for the first time for the temperature profiles in a cylindrical shape resist irradiated with an x-ray beam. A systematic parametric analysis is conducted to illustrate the effects of processing and geometric parameters on the temperature distribution and the maximum temperature rise. Based on the parametric study, the maximum allowable irradiation intensity and minimum required cooling coefficient are identified to maintain the temperature rise in the resist to within a prescribed limit. The results provide guidelines for selecting resist/substrate materials, system designs and processing parameters based on thermal transport considerations.

Nomenclature

a_n	coefficient used in the variation of parameters procedure
b_n	coefficient used in the variation of parameters procedure
Bi	Biot number
g	volumetric heat generation due to irradiation
H	layer thickness (m)
h_0	heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
I_0	x-ray intensity (W m^{-2})
k	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
k_r	thermal conductivity ratio
R_0	outer radius of the photoresist/substrate layers (m)
R_{op}	radius of the opening in the mask layer (m)
r	radial coordinate (m)
T	temperature ($^{\circ}\text{C}$)
T_{∞}	surrounding temperature ($^{\circ}\text{C}$)
T^*	dimensionless temperature
z	axial coordinate (m)

Greek Symbols

μ	absorption coefficient (m^{-1})
λ_n	eigenvalue

Superscripts/subscripts

*	dimensionless quantity
1	photoresist layer
2	substrate layer

1. Introduction

Deep x-ray lithography is an important advance over ultraviolet optical lithography in the manufacture of high aspect ratio microstructures. The process involves the irradiation of a sandwich consisting of a mask, a gap layer with gas as a cooling device and a photoresist coated substrate. The mask layer has a desired cutout pattern which selectively allows the transmission of x-rays onto the photoresist coating through the open areas of the mask. After irradiation, the parts of the coating exposed to x-rays are removed using a chemical developer such that the original pattern on the mask is replicated. Polymethylmethacrylate (PMMA) and silicon are commonly adopted as the materials for the photoresist coating and the substrate, respectively [1–5].

To facilitate the chemical development, a large x-ray dose of $2\text{--}4 \text{ kJ cm}^{-3}$ is typically required in the photoresist [6].